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ABSTRACT

Fracture mechanics is a multidisciplinary topic which is being introduced to undergraduate engineering students in such courses as materials engineering. At a recent Conference on Fracture held at the University of Waterloo, a session was devoted to fracture education. Some of the ideas presented at that session are included and discussed here. The method of teaching fracture at Waterloo is then described. This method uses a cooperative system with alternate work and study terms over a five-year period. The paper concludes by focusing on methods of teaching and their relevance to mastery of the desired information and skills. (BB)

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FRACTURE EDUCATION IN ENGINEERING^Δ

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1. INTRODUCTION

Fracture of components is a problem which has confronted engineers for generations. However, it is only during the last twenty years that large strides have been made in understanding fracture behaviour. This has involved the input of mathematicians, engineers and materials scientists. The multidisciplinary approach has proved to be essential in order to solve the problems on the microscopic and continuum levels. The main outcome of this work has been the evolution of a new discipline - fracture mechanics - which has proved to be a remarkably successful tool in the analysis of failure by brittle and fatigue fracture mechanisms.

Naturally enough, the upsurge in studies of fracture has led to its introduction into university courses, particularly where personnel in such institutions are involved in fracture research. Whereas, in the past, fracture courses were either non-existent or offered as a specialist option, nowadays in many cases the topic is introduced at an early stage of the undergraduate syllabus in such courses as materials engineering.

The multidisciplinary nature of the subject is an important factor which has to be considered in teaching fracture. Most topics in engineering syllabuses tend to be treated in isolation from other aspects of the subject, and this packaged approach of educating engineers has clear disadvantages. Therefore, the teaching of fracture can be used to emphasize the importance of integrating knowledge from various sources. However, much thought has to be given to deciding how best this may be achieved.

Several problems need to be considered in the teaching of a fracture course. Questions to be asked include: (i) at what stage of the undergraduate syllabus should it be introduced? (ii) to what level should it be

taught? (iii) what are the best techniques for teaching fracture?

At the recent International Conference on Fracture (ICF4) [1] held at the University of Waterloo, one session was devoted to fracture and education. This gave a vivid insight into the teaching of the subject at universities in various parts of the world. As a basis for this paper, some of these ideas are summarized and discussed. The method of teaching fracture at Waterloo is then described. Waterloo has adopted the co-operative system with alternate work and study terms over a five year period. The paper concludes by focussing on methods of teaching and their relevance to mastery of the desired information and skills.

2. ICF4- FRACTURE, EDUCATION AND SOCIETY

Much of the discussion at this meeting was based on two presentations, one being an interview with Sir Alan Cottrell and the other an account of a fracture course presented by the Open University in the U.K. to its students, who are all off-campus. There was also a review of the results of a questionnaire circulated to conference delegates in advance, that dealt with the topic the place of fracture in a university curriculum.

Cottrell pointed out the necessity for engineers and scientists to be aware of the social and political consequences of much of their work. He pointed out that this was particularly true in the field of fracture which is of vital importance in the safety of large scale engineering structures, the most renowned being nuclear energy plants and transportation of oil and gas by tankers and pipelines. Brittle failures on a large scale are rare events, but since they can be fatal they attract widespread public concern. Social awareness of such problems needs to

be considered in the teaching of all engineering courses but its particular relevance in the case of fracture requires special emphasis in the engineering curriculum. A second important point made by Cottrell was that much needs to be done with regard to transferring the existing knowledge concerning fracture to the service situation. In the context of education, this implies that emphasis should be placed on the application of understanding to real problems, probably at the expense of dealing in detail with the theoretical development of fracture behaviour.

A similar theme was propounded by the Open University team. They expressed a strong belief in the use of real-life situations as a basis for their course. Many of their films are recorded on site in industry and make use directly of the expertise of the people who are dealing every day with the particular aspect of fracture being discussed. Two factors emerge strongly from this approach: one is the importance of fracture and design against fracture in the engineering world, the other is the multi-disciplinary approach required to deal with failure problems.

As part of ICF4 a survey was made of the way fracture is taught in institutions throughout the world. An important point to emerge was that, in many cases, no fracture courses were offered to undergraduates. Interestingly, in later discussions at the conference it was noted that this lack of specific courses on the topic was particularly evident in France and Germany, which are countries that produce a large number of qualified engineers. In both countries, it appeared to be the case that innovation in undergraduate syllabuses was difficult and fracture was regarded as being a topic for the graduate specialist. At the other extreme, in Tohoku University, Japan,

Dr. Yokobori places heavy emphasis on the teaching of fracture to undergraduates and provides a course dealing solely with this topic - labelled "fractology". However, the consensus among other nations responding to the survey was that fracture should be part of a course, at the undergraduate level, dealing with the mechanical behaviour of materials.

In addition to formal teaching, the most common instructional techniques were case studies and group project work. Thus many teachers seem to be aware of the importance of linking fracture courses to practical situations. General involvement with practical problems in several institutions is achieved through co-operative programmes with industry. At Waterloo, for instance, engineering students spend alternate four month terms in industry.

One question - and probably the most important - is how desirable is it for undergraduate engineers to be taught a course specifically dealing with fracture. It was unfortunate and perhaps revealing that nearly all the participants in this session at ICF4 were people involved in education. Thus they were people who had a vested interest in fracture education. However, one representative of industry, Westwood of Martin Marietta Laboratories, strongly advocated that engineering students be exposed to courses in fracture. From his point of view, such courses should deal with fracture as an important industrial phenomenon and should include consideration of such factors as safety, cost and productivity besides emphasising both mechanisms and phenomenology. In addition, from his practical experience, it was essential to include consideration of environmental factors, since corrosion - assisted failure was a widespread fracture process.

The basic problem confronting all teachers is the extent to which

the needs of industry should be catered for in the overall context of educating students. Although engineering is a vocational subject, the specific needs of industry at any given time may be transitory and, in fact, the role of a university education involves developing independent thought and the ability to search out and extract the information required to solve problems. Nevertheless the advances that have been made, for example in fracture mechanics, indicate that such a topic is an essential component of instruction in design. At the moment most fracture courses are taught as part of materials or, to a lesser extent, mechanics courses, and it seems unfortunate, in the light of industrial considerations, that fracture problems are not dealt with more fully in design courses.

Perhaps the situation at the undergraduate level was best summarized by Westwood's suggestion that engineers should understand fracture well enough to know when to approach the specialist and what questions to ask of him.

3. THE TEACHING OF FRACTURE

Many factors have to be considered in devising a suitable course in fracture. Obviously the quality of the students and their engineering knowledge on entering the course is important. At Waterloo, the freshmen class is the best in Ontario if judged on the basis of average grades of entering students. The engineering faculty has built up a high reputation, particularly through its co-operative teaching programme. Students are sought after by employers and this is known by high school students and as a result the ratio of applicants to places is 3:1. Figure 1 shows the freshmen enrollment of grade 13 students for 1977; a further 10-20%

of available places are reserved for other candidates such as mature students, out of province students, etc.

All mechanical engineering students have to take two courses in materials; fracture of materials is presented as an important part of one of these courses dealing with mechanical behaviour of materials. In addition, a more advanced course is offered to final year undergraduates as part of an engineering materials option, and there are two graduate courses that emphasize fracture which qualified undergraduates may take in their final term. Here we shall confine our discussion to the presentation of fracture of materials as part of the core course in materials.

The overall syllabus for 2nd year mechanical engineers is shown in Table 1. All courses in 2A are taken before those in 2B. The first year is devoted to a grounding mainly in mathematics and physics. In the second year students start work on their engineering subjects, and it is interesting to note that most of these courses do not really get involved with practical applications at this stage. One of the reasons for introducing fracture into the materials course at this point is to get the students involved at an early stage in an area of immediate practical relevance. All students would have already worked for two terms in industry and some of them would certainly have come across fracture problems during that time.

The two materials courses referred to above have to be taken by all undergraduates (ME 15 & ME 30) and the relevant syllabuses are shown in Table 2. These courses have evolved over the years and minor changes are frequently made. However, probably the most important change which

has been made in the last few years has simply been a reversal of the order in which the courses are taken. Normally materials courses proceed with the sequence: atomic properties, crystallography, phase diagrams and then mechanical behaviour. At Waterloo, the mechanical behaviour course (ME15) is given before the microstructures course (ME30). In this way the students are introduced immediately to the practical importance of materials study. In addition ME15 is intended to complement the mechanics of deformable solids course (ME19). In the next term students move on to ME30 in which they learn how the properties of materials may be controlled by microstructural methods. Although this reversal in the presentation of materials may appear to be illogical, it has proved to be very successful. Students are more motivated to materials in general and they often see ME 15 as the most practical and relevant course that they do in the 2A term.

The fracture part of ME15 consists of six lectures out of a total of 24 in addition to laboratory work. (The syllabus for this section of the course is shown in Table 3). The relevance of each type of failure and its occurrence in practice are described. Most time is spent on brittle fracture. This topic is the most difficult to present, mainly because of the multidisciplinary approach required to understand it fully. Students appear to prefer topics to be compartmentalized into fixed areas of knowledge and it is important for them to learn that many practical problems require a multi-faceted approach.

Initially the theoretical fracture strength of materials is derived and the reasons for its non-applicability to real materials explained. This leads to the development of the Griffith equation and its modification

by Irwin and Orowan to take account of plastic flow which occurs at the tips of sharp cracks in real materials. This in turn introduces students to the concept of fracture toughness. The stress analysis approach is mentioned and the stress intensity factor is discussed which in turn leads to the plane strain fracture toughness (K_{IC}) of a material being regarded as a material property. The usefulness of knowing K_{IC} in terms of design is pointed out. After dealing with the mechanics side of the problem we then discuss the factors which affect fracture toughness, such as temperature and microstructure. Finally some of the limitations of linear elastic fracture mechanics are briefly mentioned. In addition, an Open University film on fracture toughness testing is presented.

Students are given an introduction to other forms of fracture. The phenomenology and micromechanisms of fatigue are discussed, and the importance of design against fatigue is emphasised. Creep fracture is dealt with briefly. The course concludes by considering the construction of fracture mechanism maps and their importance in extrapolation procedures. The laboratory work is closely related to the lecture course. Experiments involve fatigue, creep and impact testing as well as fracture experiments on glass and plexiglass. Students are also given case studies of failures.

The course as a whole has several objectives, some of which are related specifically to learning about fracture while others are concerned with developing the thinking capacity of the students in the particular context of "Materials in design". Fracture is not taught in isolation from other aspects of materials and, indeed, emphasis is placed on the importance of considering all the properties required in a material

for a given service application. For example, the idea of compromising between strength and fracture resistance is discussed.

One important objective is to introduce the idea that an understanding of fracture behaviour requires the consideration of several different disciplines. Thus, the problem is considered in the light of continuum mechanics and of micromechanisms. By discussing fracture in terms of engineering materials and their performance in service the practical relevance of the course is emphasized. Also the social implications of fracture control in design are mentioned; for example, the importance of leak-before-break as a design criterion, and topical examples, such as the Northern Pipeline.

The development of independent thinking is encouraged by means of written assignments and laboratory experiments. In the laboratories students are encouraged to ask questions and to think about the experiments in connection with the lecture course. The written assignments do not consist simply of numerical questions involving mathematical manipulations, as can be seen from Table 4, which shows some questions from such an assignment. Many of the questions are open-ended in the sense that the onus is put on the student to determine the depth to which the question is probed. An important aspect of this work is that the student has to search out information from various sources and integrate it into a coherent form in order to provide an adequate answer. The assignment question based on an analysis of a current research paper is especially useful in this regard. Similar approaches are encouraged by the case-studies in the laboratory in which the students are given very little information on the failure. "Correct" solutions are not expected, but by using the literature (e.g. Metals Handbook) students should be able to suggest various failure possibilities, based on the component usage, manufacturing process, etc.

The whole course is worth a half-credit to the student. Assessments are made on the basis of two written assignments, laboratory work and a term examination. The latter can earn 30% of the total so that students have to apply themselves to all the assessment work in order to get a good grade.

Analyses of the various forms of assessment are used to determine the successful and less successful aspects of the course. This often leads to minor changes. Major changes are obviously less frequent and some such changes have been discussed earlier. Over the last few years the course has become more concerned with the behaviour and problems of real engineering materials and less and less emphasis is being placed on the elegant physics of single crystal behaviour and dislocation theory. One of the important objectives of the present course is to encourage the students to think about the importance of the material in engineering problems and not to rely solely on mathematical solutions which ignore material behaviour.

When new material is introduced into a course it must be remembered that this has to be done at the expense of other topics which were previously thought to be vital to the teaching of the subject. Thus there is a tendency for the content of the course to increase with time. This occurred with the present course and the obvious result was that it was demanding more of the students time. Therefore, more recently, course refinement has also been concerned with the time and effort required on the part of the student so that different courses are more equitable in this regard. As a result areas such as crystallography and dislocation theory have been reduced and more emphasis has been placed on the main focus of the course - the performance of engineering materials in service conditions.

4. PEDAGOGICAL ASSUMPTIONS AND QUESTIONS

Implicit in these descriptions of the way fracture is taught are certain assumptions about effective teaching and learning of engineering concepts. For example, in contrast with some other subject areas studied in universities, engineering must be taught in such a way that students can apply what they have learnt to real problems in the outside world. The question of how what is learnt in one situation can be transferred and applied in another situation is referred to by psychologists as "transfer of training", and is a very basic concern of all education. Assuming general agreement that it is desirable to teach for maximum transfer, the question arises as to how best this may be accomplished. For example, is it preferable to go from the general and theoretical to the particular and applied, as in traditional, discipline-oriented university teaching, or is the reverse precept a better strategy, as claimed by proponents of the case study approach? There is common consensus (among both laymen and psychologists) that the closer the learning experience to the practical ("real life") situation, the easier it is for transfer to take place, and this would seem to be a strong argument for using genuine problems from industrial settings, or for involving students in real work experiences such as those provided in co-operative programmes.

Cottrell⁽²⁾ is one person who has argued strongly for an applied approach to the teaching of fracture with more integration of university and industrial research. And Reid et al⁽³⁾, in a similar vein, have commented on the tendency of the traditional university teacher to tell his students what he knows, regardless of its relevance to their (and society's) needs.

They have advocated a "forensic" or trouble-shooting approach, such as that used for the teaching of fracture at the Open University. Students are set empirical tasks for which there is not necessarily any single "right answer" -- in contrast to the situation in more traditional laboratory work, where there is often an undue emphasis on producing the correct results rather than on the process of learning and discovery leading to the conclusions. Not only does this method have the advantage of maximizing transferability between classroom and "the outside world" of work, but it is also believed to foster the skill of synthesis, as opposed to the analysis that is often the major concern in more traditional approaches to learning⁽⁴⁾. Synthesis is a desirable skill for most practicing engineers, but unfortunately the time required to guide students through the sophisticated process of synthesizing solutions to a problem is considerable. Not only do suitable problems have to be delineated (and the same problems cannot necessarily be used from one year to the next), but experience at the University of Waterloo has shown that the teacher often needs to be available on a daily basis to small groups of students seeking advice. A further consideration is that not all university teachers are able to respond very well in this type of learning situation, which demands quite different skills from the didactic approach normally taken in a lecture. One solution to this problem is team teaching (both to prepare the course materials as well as to teach them) and the division of responsibilities among teachers according to particular skills in teaching style as well as topics.

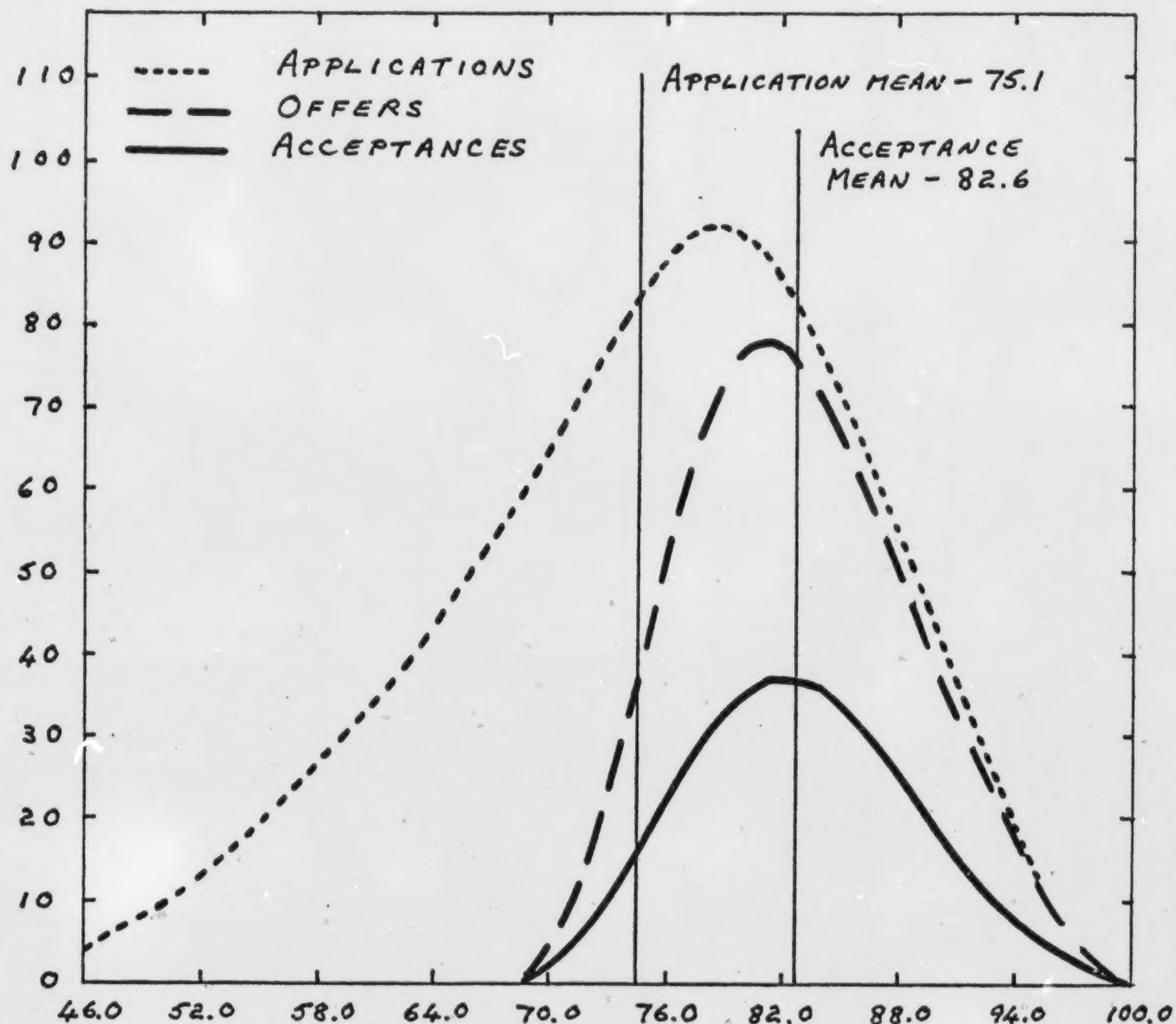
Another implication of the problem-solving approach to teaching is that the method does not permit an easy demarcation of disciplinary boundaries. Nowhere is this brought home more clearly than in the case of

fracture, which is not only a discipline but also a phenomenon that, to understand it fully, requires skills and insights from a variety of traditional disciplines. In the future it is almost certain that engineering education cannot rely solely on subject matter ease and traditional teaching methods that review students as passive receivers of transmitted information, if only because the knowledge and skills taught to university students will change even more rapidly over the careers of the present generation than they did during the past three decades. Hence the teaching of fracture, as is the case with any other applied discipline, can no longer be restricted to the mere transmission of what is known to this point: Rather, students will need to be taught a fundamental supplementary skill -- the skill of learning how to learn.

References

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- (2) Cottrell, A.H., A BBC-Open University Interview, Open University Press, Milton Keynes, 1975.
- (3) Reid, C.N., Newey, C.W.A., Reynolds, K.A., Weaver, G., and Williams, K., A Case Study Approach to the Teaching of Fracture, Fracture 1977 -- Advances in Research on the Strength and Fracture of Materials, ed. D.M.R. Taplin. Vol. 1, Pergamon Press, New York, 1977.
- (4) Bligh, D.A., What's the Use of Lectures? Penguin, Harmondsworth, 1972.

NUMBER OF STUDENTS



17
GRADE 13 AVERAGE

TABLE 1
SECOND YEAR SYLLABUS

2A

ME 200 - Introduction to Mechanical Engineering 1
ME 1 - Advanced Calculus
ME 12 - Dynamics
ME 15 - Structure & Properties of Matter 1
ME 19 - Mechanics of Deformable Solids 1
MSc.21 - Applied Probability & Statistics
EIE 14 - Electrical Engineering 1

2B

ME 3 - Ordinary Differential Equations
ME 4 - Numerical Analysis
ME 20 - Mechanics of Deformable Solids 2
ME 30 - Structure & Properties of Matter 2
ME 50 - Thermodynamics
MSc.23 - Engineering & Managerial Economics

TABLE 2

ME 15 Structure and Properties of Matter 1

1. Materials - its place in mechanical engineering and design.
2. Internal structure of materials - interatomic bonding. Defects - role in mechanical behaviour.
3. Microscopy of materials and testing methods.
4. Elasticity, anelasticity and stress - strain behaviour - uniaxial tensile and compressive behaviour.
5. Plasticity in metals and alloys - yielding, strain hardening - dislocation processes - effect of temperature. Deformation maps.
6. Fracture of materials.
7. Non-metallic behaviour - ceramics, polymers, composites, biomaterials.
8. Physical properties of materials - electrical, magnetic, optical.

ME 30 Structure and Properties of Matter 2

1. Equilibrium diagrams and phase transformations.
2. Diffusion processes
3. Non-equilibrium diagrams - TTT curves
4. Heat treatment of alloys for strengthening, etc.
5. Deformation and annealing at high temperatures - recovery
recrystallization, grain growth
6. Deformation of polymers
7. Corrosion - metals and polymers
8. Properties of concrete

TABLE 3
FRACTURE SYLLABUS

Introduction - types of fracture and examples of engineering failures

Brittle fracture - nucleation and propagation of cracks. Griffith theory.
Orowan-Irwin development. Fracture mechanics.
Importance of temperature and microstructure. Fracture
safe design. Leak-before-break.

Ductile fracture - brief outline

Fatigue - low and high strain fatigue. Phenomenology. Micromechanisms.
Factors important in controlling fatigue behaviour. Temperature
effects.

Creep - types of creep failure. Phenomenology. Micromechanisms.
Long time creep prediction.

Fracture Maps - synthesis of above to produce fracture mechanism maps.

ASSIGNMENT 2

1. A decision has recently been made (February 1978) to build in Canada a Natural Gas Pipe Line from Alaska to the Alberta/US border. The pipeline will be 56 inches in diameter and the wall thickness will be 0.54 inches and 1000 miles or so long. The material chosen is a controlled-rolled micro-alloyed steel. Discuss the materials problems involved in this choice. Where possible illustrate your answer with xerox copies of newspaper reports related to the decision.
2. What are "Deformation Mechanism Maps" and why are they important? What are the difficulties in extending this concept to "Fracture Maps".
3. Select a 1977 or 1978 research paper from the major current journals on some aspect of mechanical behaviour (including metalworking). Annotate the paper (along the lines discussed in class) and write a summary on the practical usefulness of the research.
4. Write notes illustrated by diagrams on the various techniques of fracture toughness testing, including the limitations and applications.
5. What is the plane strain fracture toughness of a material? The plane strain fracture toughness (K_{Ic}) of a steel decreases with increasing yield strength (σ_Y) as:

$$K_{Ic} = [1.5 \times 10^3 - 1.1 \sigma_Y] \text{ (MPa m}^{1/2}\text{)}$$

A thick plate of this steel is to be used for a structural application. An elastic safety factor of 0.75 is to be used such that the working stress (σ_w) can be 0.75 σ_Y without causing gross yielding. If non-destructive testing techniques are able to detect surface flaws to 5 mm $\pm$ 2.5 mm, determine the highest strength material that can be used safely without causing either gross yielding or brittle fracture.